

Degradation of glacial deposits quantified with cosmogenic nuclides, Quartermain Mountains, Antarctica

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Earth Surface Processes and Landforms

ABSTRACT: Many glacial deposits in the Quartermain Mountains, Antarctica present two apparent contradictions regarding the degradation of unconsolidated deposits. The glacial deposits are up to millions of years old, yet they have maintained their meter-scale morphology despite the fact that bedrock and regolith erosion rates in the Quartermain Mountains have been measured at 0.1–4.0 m Ma⁻¹. Additionally, ground ice persists in some Miocene-aged soils in the Quartermain Mountains even though modeled and measured sublimation rates of ice in Antarctic soils suggest that without any recharge mechanisms ground ice should sublimate in the upper few meters of soil on the order of 10³ to 10⁵ years. This paper presents results from using the concentration of cosmogenic nuclides beryllium-10 (¹⁰Be) and aluminum-26 (²⁶Al) in bulk sediment samples from depth profiles of three glacial deposits in the Quartermain Mountains. The measured nuclide concentrations are lower than expected for the known ages of the deposits, erosion alone does not always explain these concentrations, and deflation of the tills by the sublimation of ice coupled with erosion of the overlying till can explain some of the nuclide concentration profiles. The degradation rates that best match the data range 0.7–12 m Ma⁻¹ for sublimation of ice with initial debris concentrations ranging 12–45% and erosion of the overlying till at rates of 0.4–1.2 m Ma⁻¹. Overturning of the tills by cryoturbation, vertical mixing, or soil creep is not indicated by the cosmogenic nuclide profiles, and degradation appears to be limited to within a few centimeters of the surface. Erosion of these tills without vertical mixing may partially explain how some glacial deposits in the Quartermain Mountains maintain their morphology and contain ground ice close to the surface for millions of years. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: cosmogenic nuclides; Antarctica; landscape evolution; erosion rate; sublimation rate

Introduction

The Quartermain Mountains are located in the south-western section of the McMurdo Dry Valley (MDV) region of Antarctica (Figure 1), and they contain some of the oldest glacial deposits on the continent (e.g. Denton *et al.*, 1984, 1993). The glacial stratigraphy recorded in the Quartermain Mountains is central to our understanding of the history of the East Antarctic Ice Sheet for the past 11.3 Ma because the age and stability of many surface deposits found there indicate climate stability in this region since the Miocene (Denton *et al.*, 1993; Marchant *et al.*, 1993; Schäfer *et al.*, 1999). Chronologies for glaciogenic deposits in the Quartermain Mountains have been established with cosmogenic nuclides (e.g. Brown *et al.*, 1991; Brook *et al.*, 1993; Brook *et al.*, 1995; Schäfer *et al.*, 1999) and with argon-40/argon-39 (⁴⁰Ar/³⁹Ar) ages of *in situ* volcanic ashes (e.g. Marchant *et al.*, 1993; Sugden *et al.*, 1995; Lewis *et al.*, 2007). Many of the glacial deposits are millions of years old,

yet they have maintained their meter-scale morphology despite the fact that bedrock and regolith erosion rates in the Quartermain Mountains are 0.1–4 m Ma⁻¹ (Summerfield *et al.*, 1999; Putkonen, *et al.*, 2008a).

Another intriguing feature of glacial deposits in the Quartermain Mountains is that buried glacial ice underlies the Granite Drift in central Beacon Valley, and based on the superposition of an 8.1 Ma ash deposit, this ice is thought to be Miocene in age (Sugden *et al.*, 1995). The stability of ground ice in the MDV, in the form of both relict glacial ice and ice-cemented soil, is an area of ongoing research. Presently, sublimation rates of bare ice in the MDV are on the order of 10⁴ to 10⁵ m Ma⁻¹ (Clow *et al.*, 1988) and many authors have modeled and measured sublimation rates of ice through a soil layer in various parts of the MDV. Most of the measurements and models suggest that ground ice in the MDV should be actively subliming, and that the upper few meters of soil in the MDV should be ice-free on the order of 10³ to

10^5 years (Hindmarsh *et al.*, 1998; McKay *et al.*, 1998; Campbell and Claridge, 2006; Bockheim *et al.*, 2007; Hagedorn *et al.*, 2007), but recent models have shown that small variations in cloud cover, relative humidity, and snow cover can cause near equilibrium conditions and allow for the long term stability of ground ice (Schorghofer, 2005; Kowalewski *et al.*, 2006; McKay, 2009). Although these models disagree as to whether or not ice in soils in the MDV should be actively subliming or are near equilibrium and stable, the observation remains that ground ice persists near the surface within Miocene-aged soils in the Quartermain Mountains (Bockheim, 2007).

The primary objective of this paper is to quantify degradation rates for glacial deposits in the Quartermain Mountains. In this paper, we will use the term degradation to mean the general lowering of Earth's surface, regardless of process. We are motivated by the apparent conflict between the persistence of landforms that are eroding at rates on the order of a few meters per million years while maintaining their meter-scale morphology, and the presence of ground ice in Miocene-

aged soils in the MDV. To accomplish our objective, we will use the concentration of cosmogenic nuclides beryllium-10 (^{10}Be) and aluminum-26 (^{26}Al) from meter deep vertical sections in glacial tills to examine how quickly and by what geomorphic processes glacial deposits in the Quartermain Mountains degrade.

Field Area

The Quartermain Mountains, Antarctica contain five main valleys, the largest of which are Beacon (215 km²) and Arena (68 km²) (Figure 1). Bedrock in the valleys consists of Devonian-Triassic sandstones of the Beacon Supergroup and Jurassic sills and dikes of the Ferrar Dolerite (Barrett, 1981). The general climate of the area is a hyper-arid, cold-polar desert. The mean annual temperature on the floor of Beacon Valley is -24°C (Putkonen *et al.*, 2003), and water-equivalent precipitation is probably less than 10 mm yr⁻¹ (Bockheim, 2007). Based on the dominant active geomorphic processes

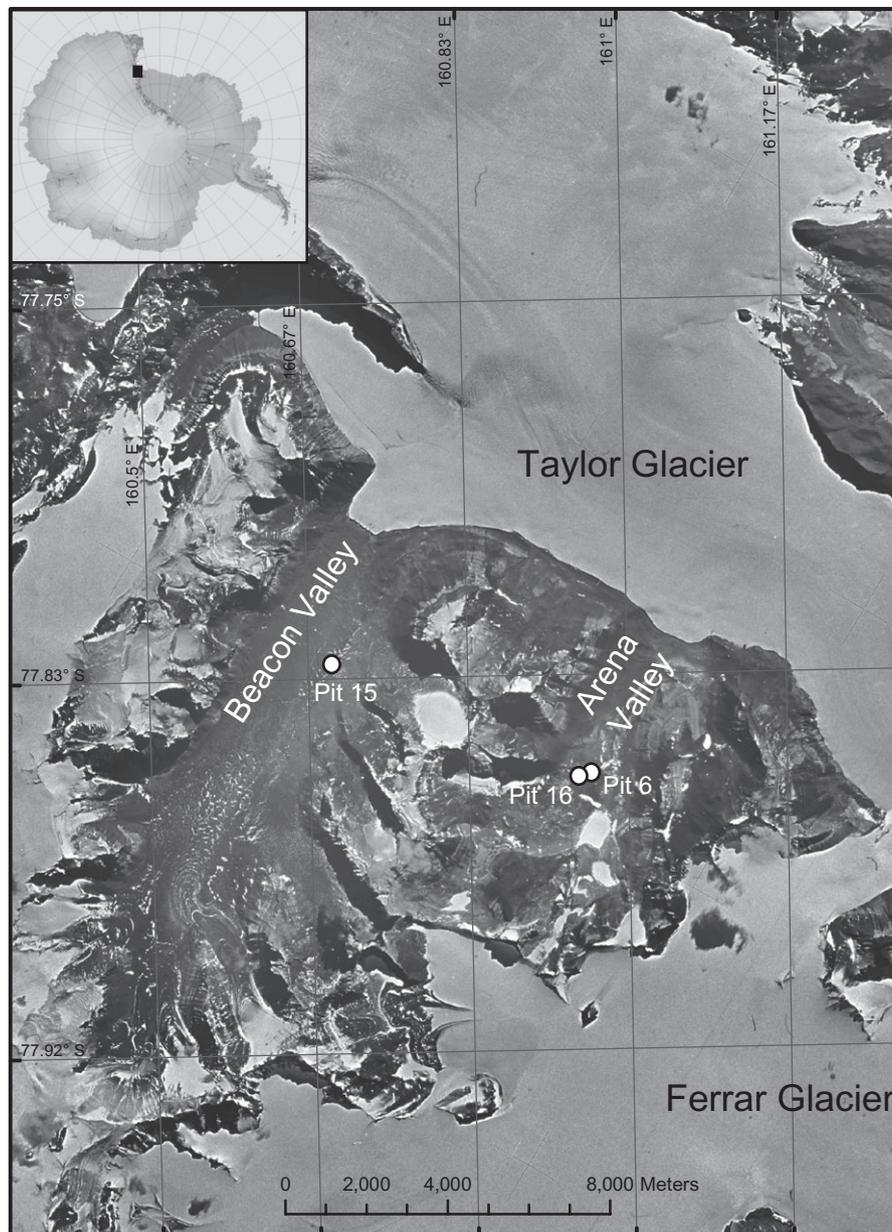


Figure 1. Inset: Map of Antarctica, showing the Quartermain Mountains in the dark rectangle. Satellite image of the Quartermain Mountains showing the three sample sites.

and equilibrium landforms that would form under these processes, Marchant and Head (2007) defined microclimate zones in the MDV and the Quartermain Mountains in the coldest and driest area, the stable upland zone.

The Quartermain Mountains contain a number of well mapped glaciogenic surface deposits and bedrock landforms that reflect the expansion of Taylor Glacier, overriding of the entire range by northeast-flowing glaciers and ice sheets, and the growth of local alpine glaciers (Denton *et al.*, 1984; Marchant *et al.*, 1993). With detailed geomorphic mapping and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of *in situ* ash deposits, Marchant *et al.* (1993) determined relative and absolute chronologies for most of the surface deposits in Arena Valley and found that the oldest deposits in Arena Valley are >11.3 Ma. The mouth of Arena Valley shows a series of arcuate moraines that open to Taylor Glacier and boulders on these moraines have been dated with cosmogenic nuclides and yield ages from 0.12 to 2.2 Ma (Brown *et al.*, 1991; Brook *et al.*, 1993). Boulders from the Quartermain I till that reflect older expansions of Taylor Glacier have ages up to 3 Ma (Brook *et al.*, 1995). Cosmogenic nuclide dates for clasts in the Granite Drift that overlies the relict glacial ice in Beacon Valley range from 1.18 Ma (Marchant *et al.*, 2002) to 2.3 Ma (Schäfer *et al.*, 2000). Ng *et al.* (2005) re-interpreted these clast ages as minimum sublimation rates averaging $>7 \text{ m Ma}^{-1}$ and that the lower 80% of the Granite drift formed in the past 43–310 ka. Because of the age of many of these deposits, the glacial stratigraphy recorded in the Quartermain Mountains is one line of evidence in the MDV that supports the argument that the MDV have remained cold and hyperarid since the mid-Miocene (e.g. Sugden *et al.*, 1993; Lewis *et al.*, 2007).

Sample sites

We sampled three different glacial deposits at three separate sites in the Quartermain Mountains (Figure 2). Because exposure dating techniques with cosmogenic nuclides depends on the geologic setting to constrain the analysis, we will describe each sample site in detail here. The important aspects of these descriptions are details that provide evidence of the nature of exposure that the samples have experienced, such as geomorphic processes active at these sites. Additionally, we want to glean any available information about the inherited nuclide concentrations in each deposit that accumulate during prior exposure of the samples before they were deposited at the sample site.

In Beacon Valley, we sampled an undated moraine on the southwest flank of the mouth of the valley (04-BV-Pit 15: 77.82970°S, 160.69083°E, 1370 m). Bockheim (2007) correlated this moraine with either the Taylor IVa (0.75 Ma) or IVb (1.7 Ma) moraines identified in Arena Valley (Brook *et al.*, 1993). Brook *et al.* (1993) initially reported ages of 1.0 Ma (Taylor IVa) and 2.2 Ma (Taylor IVb) for these moraines, but these results do not take into account the persistently low Antarctic air pressure that causes nuclide production rates to be 25–30% higher in Antarctica, which results in younger surface exposure ages (Stone, 2000). For this reason, we will consider the ages from Brook *et al.* (1993) to be 25% lower than reported. Based on a detailed description of the textural characteristics of these units, Marchant *et al.* (1993) determined that cold-based ice deposited the Taylor Drifts in Arena Valley. The sample site is at the crest of the moraine (Figure 2A), and we collected four samples to a depth of 60 cm. We did not encounter any ground ice at this site.

Though we do not know exactly when this moraine in Beacon Valley was deposited, we can determine some of the

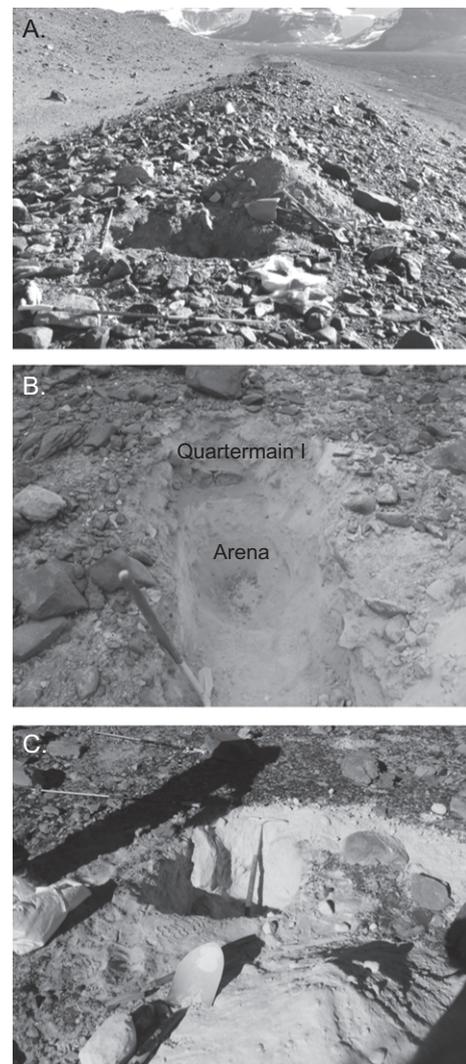


Figure 2. Photographs of the three sample sites. (A) 04-BV-Pit 15: Beacon Valley moraine. (B) 04-AV-Pit 6: Quartermain I till overlies Arena till. The two tills are separated by a buried desert pavement, and are easily distinguished because the Arena till is comprised of much more quartz sand and is much lighter in color. (C) 04-AV-Pit 16: Arena till.

processes that have been active at this site. A desert pavement caps the moraine surface today, and although desert pavements do sometimes form by the inflation of eolian sands below a gravel armor (e.g. McFadden *et al.*, 1987; Wells *et al.*, 1995; Pelletier *et al.*, 2007), there is no evidence of inflation at this site. Rather, the pavement caps the poorly sorted till abruptly, indicating that the pavement formed as a lag and that this site has experienced some erosion since it was deposited. Because the deposit is a till, we can assume that it was well-mixed when it was initially deposited, so we will assume that any inherited nuclides the samples contained due to exposure before deposition in the moraine are also well mixed.

In Arena Valley we sampled the Arena and Quartermain I tills. These units have been described in detail by Marchant *et al.* (1993), and both of these drifts crop out as patchy, thin deposits with very little, if any, surface expression. Using cosmogenic nuclides, Brown *et al.* (1991) initially dated the Quartermain I till as >4.4 Ma, but Brook *et al.* (1995) later revised the age of this till to >3 Ma. However, these measurements did not adjust for the persistently low Antarctic air pressure that causes ages to be about 25% lower than initially

reported (Stone, 2000). In this study we will consider the limiting age of the Quartermain I till to be >2.3 Ma, which is the scaled value of the revised age that Brook *et al.* (1995) report. Based on stratigraphic relationships and soil properties, Marchant *et al.* (1993) found that the Arena till is >11.3 Ma. As documented by Marchant *et al.* (1993), the Quartermain I till overlies the Arena till, and the two units are separated by a buried, *in situ*, desert pavement. Based on the Quartermain I till characteristics and the observation that it did not disturb the desert pavement that caps the Arena till, Marchant *et al.* (1993) determined that cold-based ice deposited the Quartermain I till. We sampled both tills at a site that showed this stratigraphic contact (04-AV-Pit 6: 77.85500°S, 160.95928°E, 1350 m). We collected three samples in a vertical section from each till at this site for a total of six samples to a maximum depth of 88 cm. The buried desert pavement is not parallel to the modern slope and was found at a depth of 33 to 35 cm. We did not encounter any ground ice in either unit at this site.

The Pit 6 sample site (Figure 2B) presents an unusual geologic scenario where the Quartermain I till overlies the Arena till, and an undisturbed, *in situ* desert pavement separates the two units. The Arena till was deposited >11.3 Ma and was at the surface long enough to form a tightly knit desert pavement. After this exposure, the Arena till was buried for some time by the Taylor Glacier that deposited the Quartermain I till (>2.3 Ma) on top of the desert pavement that caps the Arena till. The Quartermain I till is itself capped by a desert pavement. Both of the desert pavements at this site indicate erosion because they cap each till unit abruptly and there are not buried layers of eolian sands that would indicate the pavement formed by inflation. When each drift was initially deposited, the inherited nuclides in each unit were likely well-mixed because each deposit is a poorly sorted till. However, by the time that the Quartermain I till was deposited, the nuclide concentration in the Arena till would have reflected the amount of time and erosion rate it experienced while at the surface.

The Arena till crops out at the surface in a few places in Arena Valley and we sampled just this unit at another site (04-AV-Pit 16: 77.85487°S, 160.95110°E, 1329 m). It is not clear if the Quartermain I till never covered this site (Figure 2C), or if erosion has removed it, but it is clear that the site has experienced erosion because the till is abruptly capped by a desert pavement. Given the great age of this deposit (>11.3 Ma), any inherited nuclides from exposure before the till was laid should have decayed to essentially zero, but we can assume that any inherited nuclides were initially well-mixed because the deposit is a poorly sorted till. Based on the texture of the till, Marchant *et al.* (1993) determined that wet-based ice deposited the Arena till. We collected four samples from a vertical section of the Arena till, down to a maximum depth of 60 cm, and did not encounter any ground ice during the excavation.

Methods

Sample collection and processing

In the field, we collected a series of bulk sediment samples from a hand-dug soil pit. At all sample sites we collected a sediment sample from just below the modern desert pavement that armored each site, and a series of till samples at various depths below the ground surface. We did not encounter ice-cemented soil at any of the sites. Site elevations were determined by repeated barometric pressure measurements, which

were tied to differential global positioning system (GPS) markers. The cosmogenic exposure geometry of each site was determined with a clinometer and compass.

Before isolating quartz from the samples for cosmogenic nuclide analysis, we measured the density of the tills by packing the sediment samples into a container of known volume and then measuring the mass of the packed sediment. For quartz extraction, we used the 0.3–0.5 mm grain size fraction, which was purified by heavy-liquid mineral separation and repeated etching in 2% hydrogen fluoride (HF). We extracted beryllium and aluminum from the quartz using standard methods (Stone, 2004) and measured $^{10}\text{Be}/^9\text{Be}$ and $^{27}\text{Al}/^{26}\text{Al}$ isotope ratios at the PRIME laboratory at Purdue University in West Lafayette, IN. The combined carrier and process blanks contained $1.67 \pm 0.462 \times 10^5$ atoms ^{10}Be and $0 \pm 2.04 \times 10^5$ atoms ^{26}Al . These are always less than 0.4% of the measured ^{10}Be atoms and 0.1% of the measured ^{26}Al atoms.

The beryllium isotope ratios were originally referenced to the ICN standard, which used an older and no longer accepted value for the half-life of ^{10}Be . Although there is currently some refining of the ^{10}Be half-life (Chmeleff *et al.*, 2009; Korschinek *et al.*, 2009), we have used the most common value in this paper. We renormalized the ^{10}Be measurements to the 07KNSTD (Nishiizumi *et al.*, 2007) and used the corresponding ^{10}Be decay constant ($5.1 \pm 0.26 \times 10^{-7} \text{ yr}^{-1}$, which calculates to a half-life of 1.36 Ma) in our analysis. For aluminum, the isotope ratios were referenced to the Nishiizumi (2004) standard. The sample depths, densities, and updated nuclide concentrations are found in Table I. We determined the ^{10}Be and ^{26}Al production rates at the sample sites using the method of Stone (2000), and we renormalized the ^{10}Be production rates for each site to make them consistent with the updated beryllium isotope reference following Nishiizumi *et al.* (2007). The site specific scaling factors and updated nuclide production rates are given in Table II.

Cosmogenic nuclide concentration analysis

The general concept for analyzing the cosmogenic nuclide measurements is to use the local geologic and geomorphic context to determine what happened geologically. We can then construct an exposure model to describe these geologic events and use the ^{10}Be and ^{26}Al concentrations to determine when and how fast the geologic events occurred. The concentration of cosmogenic nuclides, $N_{i,j}$, in samples that are experiencing steady erosion can be described by (Lal, 1991):

$$N_{i,j}(\varepsilon, t) = N_{i,\text{inh}} + \frac{P_i \cdot e^{-z/\Lambda}}{(\lambda_i + \varepsilon/\Lambda)} \cdot (1 - e^{-(\lambda_i + \varepsilon/\Lambda)t}) \quad (1)$$

The subscript i refer to the nuclide of interest, either ^{10}Be or ^{26}Al , and the subscript j refer to the individual samples at each site, N is the concentration of the nuclide (in atoms $\text{g}^{-1}_{\text{quartz}}$), $N_{i,\text{inh}}$ is the inherited concentration of the nuclides that remain in the till today (in atoms $\text{g}^{-1}_{\text{quartz}}$), P_i is the surface production rate of nuclide i (in atoms $\text{g}^{-1}_{\text{quartz}} \text{ yr}^{-1}$), z is the shielding mass of sample j (in g cm^{-2}), λ is the decay constant for nuclide i (in yr^{-1}), ε is the erosion rate (in $\text{g cm}^{-2} \text{ yr}^{-1}$), Λ is the attenuation length (in g cm^{-2}), and t is the exposure duration (in years). For each sample, we compute the effective shielding mass (Table I), which is the point where the nuclide production rate equals the mean production rate through the thickness of each sample, and simplifies the model calculations.

Table I. Depth, density, effective shielding mass and isotope data for the samples

Sample ID	Depth in soil (cm)	Soil density (g cm ⁻³)	Effective shielding mass (g cm ⁻²)	¹⁰ Be × 10 ⁶ ± 1 standard deviation (at g ⁻¹ quartz)	²⁶ Al × 10 ⁶ ± 1 standard deviation (at g ⁻¹ quartz)
<i>04-BV-Pit 15: Beacon moraine</i>					
04-BV-Pit 15 0-3	0-3	1.78	2.75	11.8 ± 0.220	61.7 ± 2.18
04-BV-Pit 15 18-22	18-22	1.90	36.8	9.24 ± 0.228	49.1 ± 1.87
04-BV-Pit 15 35-40	35-40	1.89	69.0	7.02 ± 0.202	38.0 ± 1.38
04-BV-Pit 15 55-60	55-60	1.81	106	5.55 ± 0.148	25.3 ± 1.20
Mean density		1.84			
<i>04-AV-Pit 6: Quartermain I overlies Arena till</i>					
04-AV-Pit 6 2-5	2-5	1.90	6.6	19.8 ± 0.895	81.6 ± 2.58
04-AV-Pit 6 18-22	18-22	1.98	37.6	16.2 ± 0.478	66.5 ± 2.51
04-AV-Pit 6 30-35	30-35	2.07	61.1	12.3 ± 0.320	51.9 ± 1.83
04-AV-Pit 6 33-37	33-37	1.74	65.8	10.4 ± 0.289	47.2 ± 1.79
04-AV-Pit 6 66-69	66-69	1.78	127	7.24 ± 0.295	32.7 ± 1.51
04-AV-Pit 6 84-88	84-88	1.80	162	5.95 ± 0.197	26.4 ± 1.04
Mean density		1.88			
<i>04-AV-Pit 16: Arena till</i>					
04-AV-Pit 16 0-2	0-2	1.70	1.69	10.0 ± 0.328	58.1 ± 1.65
04-AV-Pit 16 14-16	14-16	1.66	25.4	9.52 ± 0.263	45.7 ± 2.09
04-AV-Pit 16 29-31	29-31	1.71	50.7	6.78 ± 0.205	36.7 ± 1.57
04-AV-Pit 16 52-54	52-54	1.70	89.6	5.58 ± 0.139	29.8 ± 1.11
Mean density		1.69			

Table II. Nuclide production values at each sample site

Sample site	Latitude (°S)	Longitude (°E)	Elevation (m a.s.l.)	Shielding correction	<i>P</i> ₁₀ (at g ⁻¹ yr ⁻¹)	<i>P</i> ₂₆ (at g ⁻¹ yr ⁻¹)
04-AV-Pit 6	77.85500	160.95928	1350	0.994	19.4	131.5
04-BV-Pit 15	77.82970	160.69083	1370	0.996	19.7	133.8
04-AV-Pit 16	77.85487	160.95110	1329	0.993	19.0	129.1

In this study, we used an attenuation length of 150 g cm⁻², which is the generally accepted value for use in Antarctica [see Gosse and Phillips (2001) for a detailed discussion on attenuation lengths], and decay constants of $\lambda_{10} = 5.1 \times 10^{-7} \text{ yr}^{-1}$ for ¹⁰Be (Nishiizumi *et al.*, 2007) and $\lambda_{26} = 9.78 \times 10^{-7} \text{ yr}^{-1}$ for ²⁶Al (Nishiizumi, 2004). Because the depth of each sample is less than 1 m, we will assume that production of ¹⁰Be and ²⁶Al is entirely by spallation (Gosse and Phillips, 2001). Also, we have written the erosion rate in units of g cm⁻² yr⁻¹, which is the shielding mass removed per year. The shielding mass is the depth times the density of the material and using these units allows us to consider the degradation at a site in terms of mass removed, which makes it easier to consider the effects of erosion and sublimation of ground ice. We will convert these degradation rates and report results as m Ma⁻¹ because these units are more commonly used by geomorphologists.

Sublimation till exposure model

Because many moraines in the MDV are initially deposited as ice-cored deposits (Debenham, 1921; Hall *et al.*, 1993; Denton and Marchant, 2000) and because the Granite Drift in Beacon Valley is a sublimation till that formed as a lag as the underlying ice sublimed away (Sugden *et al.*, 1995), we must consider the possibility that at sometime in the past the glacial deposits we sampled contained either massive ice or ground ice that has subsequently sublimed away. We are invoking sublimation as the method for ice degradation, and not melting, because the climate in the Quartermain Mountains promotes sublimation of ice, and all of the sample sites lack

morphological features related to liquid water. Exposure models considering the buildup of till by the sublimation of dirty ice have been described by Schäfer *et al.* (2000) and Ng *et al.* (2005), but neither of these studies considered the case that the till was also undergoing erosion. Because all three of our sample sites are abruptly capped by a desert pavement, indicating that the pavement formed as a lag during erosion at the site, it is apparent that these sites have experienced erosion, so we must include erosion in the model that describes the sublimation of debris-laden ice.

The basic concept behind the sublimation till exposure model is shown in Figure 3(A). Initially, a till is deposited as dirty ice with a volume percent of debris in the ice. As the ice sublimates, the debris in the ice forms a lag deposit on the surface, called sublimation till. Over time, both sublimation of the dirty ice and erosion of the overlying sublimation till continue to degrade the deposit. Figure 3(B) shows how this conceptual model translates to a mathematical model for cosmogenic nuclide analysis. The samples we collected were initially deposited at a greater depth because they were shielded by both ice and debris. While the samples were in ice, they approached the surface at a rate equal to the ice sublimation rate plus the surface erosion rate because both of these processes were occurring simultaneously. Once the ice front moves past a sample, the sample accretes into the till, and the sample approaches the surface at a rate equal to only the surface erosion rate.

The concentration of nuclides predicted by this exposure model are the sum of the inherited nuclides remaining in the till today, plus the nuclides accumulated while the sample was in the ice (which will begin to decay once the sample is accreted into the till), plus the nuclides accumulated while the

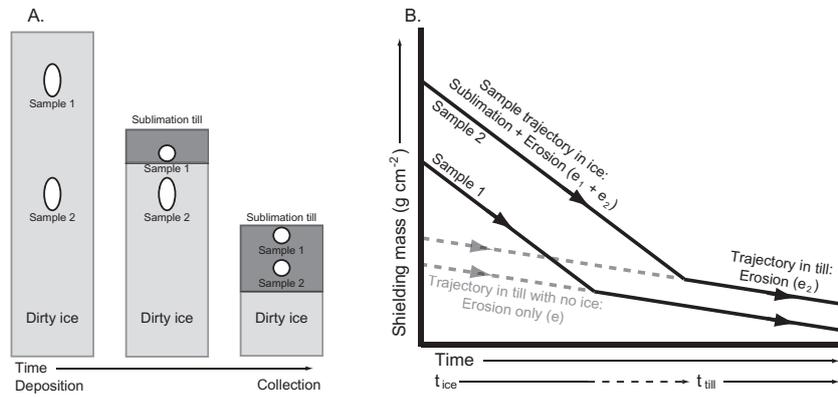


Figure 3. (A) The conceptual model for the formation of sublimation till. The deposit begins as dirty ice containing a volume percent of debris. As time passes, sublimation of the ice creates a lag deposit, the sublimation till, and erosion slowly lowers the surface of this till. (B) The shielding versus time plot for the sublimation exposure model in a reference frame that is fixed to the surface. The solid lines denote the mass that shields each sample through time. Initially, the samples are shielded by both the overlying debris and ice, and the samples approach the surface at a rate equal to the sum of these processes. Samples remain in the ice until the ice front has passed below the sample, at which point the sample accretes into the till, and it approaches the surface at a rate equal to erosion alone. The dashed grey lines represent the change in shielding that the samples would have had if there was no ice in the deposit and the site was subject to erosion alone.

sample was in the till. This can be described by the following equation:

$$N_{i,j}(\epsilon_1, \epsilon_2, t_{ice}, t_{till}) = N_{i,inh} + \frac{P_i \cdot e^{-\frac{z_j}{\Lambda}}}{(\lambda_i + (\epsilon_1 + \epsilon_2)/\Lambda)} \cdot (1 - e^{-(\lambda_i + (\epsilon_1 + \epsilon_2)/\Lambda) \cdot t_{ice}}) \cdot e^{-\lambda_i \cdot t_{till}} \dots + \frac{P_i \cdot e^{-\frac{z_j}{\Lambda}}}{(\lambda_i + \epsilon_2/\Lambda)} \cdot (1 - e^{-(\lambda_i + \epsilon_2/\Lambda) \cdot t_{till}}). \quad (2)$$

Here ϵ_1 is the sublimation rate and ϵ_2 is the erosion rate (in $\text{g cm}^{-2} \text{ yr}^{-1}$). The two time variables, t_{ice} and t_{till} , are the amount of time that each sample spends in the ice and till, respectively, and must sum to equal the age of the deposit t_i . To solve Equation 2, we must know t_{ice} and t_{till} for each sample, and to determine these values we need to know the original condition of the deposit, including the amount of ice and the concentration of debris in this ice, C_0 .

We reconstruct the original condition of the deposit by finding the combination of sublimation rate, erosion rate, concentration of debris in the ice, and age of the deposit that results in the samples having the shielding mass where we collected them. Once we know the initial amount of ice that shielded each sample, then, the amount of time that each sample spends in ice, t_{icer} is the amount of time it takes to remove this ice for some sublimation rate, ϵ_1 . Thus, t_{icer} can be described by:

$$t_{ice}(\epsilon_1, \epsilon_2, C_0, t_i) = \frac{(z_j + \epsilon_2 \cdot t_i) \cdot (1 - C_0) \cdot \rho_{ice}}{C_0 \cdot \rho_{till} \cdot \epsilon_1}. \quad (3)$$

In Equation 3, z_j is the shielding mass of sample j where we collected it, ρ_{ice} is 0.92 g cm^{-3} and ρ_{till} is the average measured density of the unit (Table I). The time that each sample spends in the till is simply $t_{till} = t_i - t_{icer}$. Thus, to solve Equation 2 for each nuclide we really have five unknowns: the inherited ^{10}Be or ^{26}Al , the sublimation rate, the erosion rate, the initial debris concentration in the ice and the age of the deposit.

There are some additional constraints that need to be added to this exposure model to make it physically valid. One constraint on the model is that the sublimation rate needs to be

faster than the erosion rate, or else there would be ice at the surface. Additionally, because we did not encounter ground ice at any of the sites, the sublimation rate needs to be fast enough that the ice front is below the depth of our lowest sample. The easiest way to enforce this is to ensure that the t_{till} for all samples is >0 :

$$t_{till} = t_i - \frac{(z_j + \epsilon_2 \cdot t_i) \cdot (1 - C_0) \cdot \rho_{ice}}{C_0 \cdot \rho_{till} \cdot \epsilon_1} > 0. \quad (4)$$

For the inherited nuclides, we need to make sure that the ratio of ^{26}Al to ^{10}Be lies within the permissible region (Klein *et al.*, 1986), so the final constraint is that:

$$\frac{1}{\lambda_{10}} \cdot \ln \left[1 - \frac{N_{10,inh} \cdot \lambda_{10}}{P_{10}} \right] \leq \frac{1}{\lambda_{26}} \cdot \ln \left[1 - \frac{N_{26,inh} \cdot \lambda_{26}}{P_{26}} \right]. \quad (5)$$

The constraint on the inherited nuclides described by Equation 5 is applied to both the erosion and sublimation exposure models.

Error analysis

To solve for the unknowns in Equations 1 and 2, we find the combination of parameter values that produce the least difference between the observed and modeled concentration profiles and satisfy all the earlier mentioned conditions. We compare this prediction with the measured nuclide concentrations using an error-weighted chi-square fit and we minimize the chi-square fit using standard optimization techniques in the MATLAB® software. Optimizing the parameters for the lowest chi-square value can be challenging because Equations 1 and 2 are non-linear and asymptotic in behavior for large time values, but avoiding local minima solutions can be addressed by using appropriate starting values for the parameters in the optimization process.

To determine the uncertainties for these results, we carried out a 10 000 run Monte Carlo simulation that took into account uncertainties in the measured nuclide concentrations. This method assumes that the measured nuclide concentrations are a Gaussian distribution with the one-sigma errors reported in Table I, and a detailed explanation can be found

in Balco *et al.* (2005). Each run in the Monte Carlo simulation takes a random value for each data point from this Gaussian distribution, and finds the best fit parameters to this set of data points. This exercise yields a histogram of possible solutions for the unknowns in the exposure models, from which we report the 68% confidence interval as the error of the best-fit parameters. Because there are many unknowns in Equation 2, the results from the Monte Carlo simulation are rarely a normal distribution, in which case we report the errors as a \pm range about the mode.

Limiting the time-period of measurements

Although Equations 1 and 2 contain both time and degradation rate variables, a common problem in cosmogenic nuclide analysis is that nuclide concentrations reach equilibrium between production and decay, meaning that we cannot always uniquely solve for both the age and degradation rate (Gillespie and Bierman, 1995). The period of time that it takes cosmogenic nuclide concentrations to reach equilibrium with an erosion rate is controlled by the effective half-life:

$$\tau_{1/2,e} = \frac{\ln(2)}{(\lambda_i + \varepsilon/\Lambda)}, \quad (6)$$

where ε is the degradation rate of the overlying sediments. After a several effective half-lives have passed, the ^{10}Be and ^{26}Al will have reached equilibrium with steady degradation, after which we can only confidently state the degradation rate and not the age of the deposit. In this case, we will report that the degradation rate has gone on at a site for a time period equal to a few effective half-lives.

Furthermore, the effective half-life controls the timescale of changes in the degradation rate that the measurements record. Changes in the degradation rate that are on much shorter timescales than the effective half-life will cause only small variations in the nuclide concentrations relative to the long-term erosional equilibrium concentration value (Balco and Shuster, 2009). This means that if the effective half-life is on the order of 10^5 to 10^6 years, then even changes in the erosion rate on the order of 10^4 years will not significantly affect the measured nuclide concentration. Even though degradation rates are not likely to be steady over 10^5 – 10^6 years, if degradation rates are low and the effective half-life is long, then the measured nuclide concentrations will reflect the long-term average degradation rate over these timescales.

Results

Figure 4 shows the nuclide concentrations for each pit plotted with a line representing the expected nuclide concentrations for an erosion rate that matches the concentration of the uppermost sample in each till. For a stable, or steadily eroding till with no vertical mixing (Equation 1), the predicted nuclide concentrations should fall along a curve with an e-folding length equal to the attenuation length, 150 g cm^{-2} . Inherited nuclides, due to prior exposure before the deposition of the till, will increase the concentration of cosmogenic nuclides in the samples, and the resulting expected nuclide concentration curve will be steeper and decrease less rapidly with shielding mass than if no inherited nuclides remain in the samples today. In contrast, the sublimation and erosion exposure model (Equation 2) predicts lower nuclide concentrations at depth than Equation 1 because the lower samples have spent more time in ice than the upper samples, and have subse-

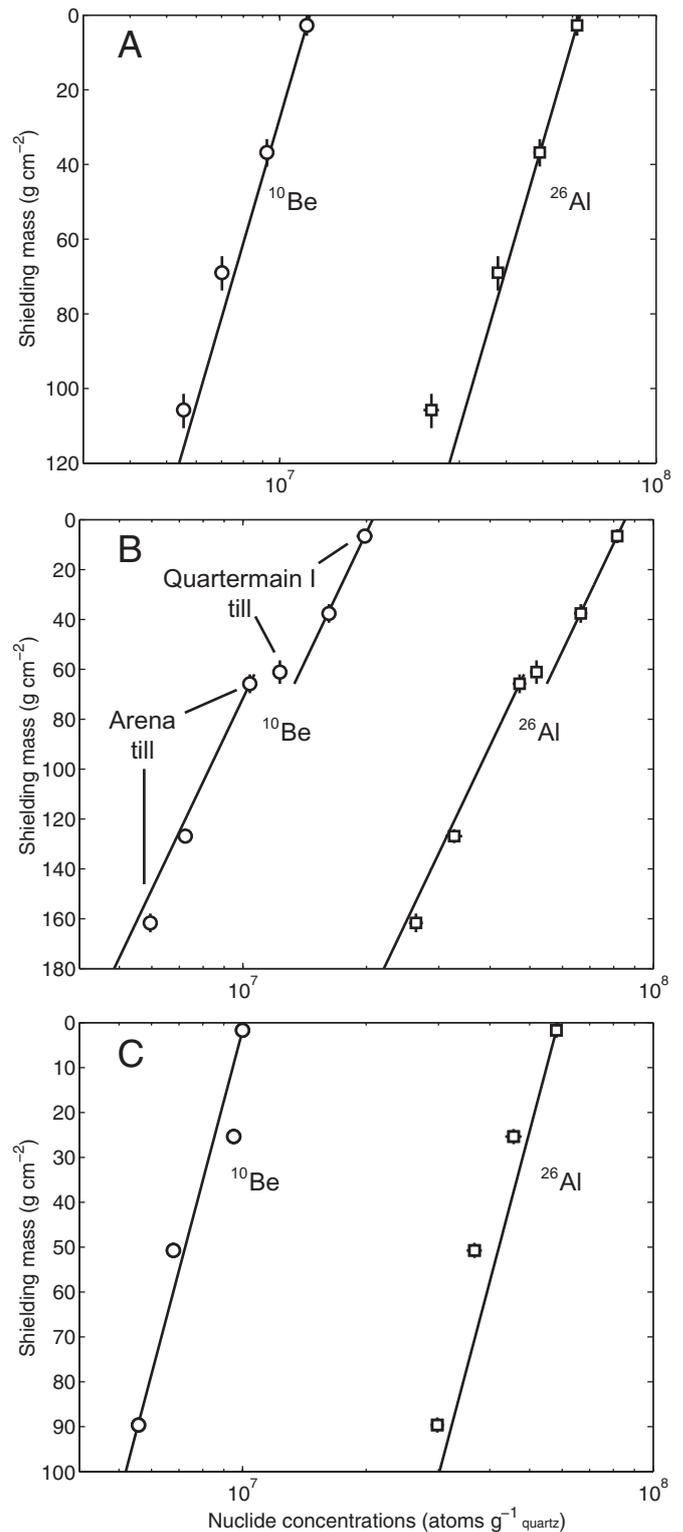


Figure 4. Measured ^{10}Be (circles) and ^{26}Al (squares) concentrations (in atoms $\text{g}^{-1}_{\text{quartz}}$) in each depth profile. For each data point, the small vertical lines show the depth range for each sample in the profile, and the small horizontal lines show the one-sigma error for each measurement. In some cases, these lines are smaller than the data points on the scale shown. The solid lines show the predicted nuclide concentration for the erosion rate indicated by the concentration of the surface sample. (A) 04-BV-Pit 15: Beacon moraine. (B) 04-AV-Pit 6: Quartermain I till overlies Arena till. (C) 04-AV-Pit 16: Arena till.

quently been shielded from the cosmic ray flux by more mass (Schäfer *et al.*, 2000; Marchant *et al.*, 2002; Ng *et al.*, 2005).

The lower samples in Pit 15 (Beacon Valley moraine) and the Quartermain I till samples at Pit 6 have lower nuclide

concentrations than expected for a steadily eroding profile, which is characteristic of a till that formed at least partially as a lag from the sublimation of debris-laden ice. The Arena till samples in the lower section of Pit 6, fall directly on a curve for a steadily eroding profile, which indicates that this unit at this site has not had any ice sublimate during the time period that these samples record (~2 Ma). For the Arena till samples at Pit 16, which is where the Arena till crops out at the surface, the ^{26}Al concentrations are lower than predicted by erosion alone, but the ^{10}Be concentrations do not show this pattern, which may indicate either sublimation of ice in this till or a large amount of inherited ^{10}Be remaining in the samples or sublimation of this. The following sections will explore the results for each site in more detail.

Beacon Valley moraine (04-BV-Pit 15)

The nuclide concentrations at this site are not well explained by erosion and are characteristic of a till that formed by sublimation of debris-laden ice (Figure 4A). The best-fit results for Equation 2 are that the moraine was deposited 0.53–0.1/+0.2 Ma ago as a deposit of dirty ice with a debris concentration of 12–2/+1%. This ice sublimated at a rate of $12 \pm 2 \text{ m Ma}^{-1}$ and the till that formed as a result of the sublimation eroded at a rate of $0.4 \pm 0.1 \text{ m Ma}^{-1}$. Under these degradation rates, the lowest sample at this site emerged from the ice 27 ka ago. The inherited nuclide concentrations remaining in the till today are $4.1 \pm 0.17 \times 10^6 \text{ atoms g}^{-1}_{\text{quartz}}$ for ^{10}Be and $17 - 0.99/+0.42 \times 10^6 \text{ atoms g}^{-1}_{\text{quartz}}$ for ^{26}Al . These parameters fit the measured concentrations with a chi-square value of 3.2, which is a significant improvement over the erosion exposure model (erosion rate = 1 m Ma^{-1} for the past ~3 Ma, chi-square value of 27). The predicted nuclide concentrations for both exposure models are shown in Figure 5.

Though this age for the moraine is consistent with the range of ages for the Taylor moraines in Arena Valley (0.1–1.7 Ma), we cannot confidently determine a unique age for this moraine because the nuclide concentrations have reached equilibrium with the sublimation rate and only reflect the degradation rates. Under a sublimation rate of 12 m Ma^{-1} the effective half-life of ^{10}Be and ^{26}Al is on the order of 10^5 years, so the nuclide concentrations will reflect only the sublimation rate and not the age of the moraine once ~0.4 Ma have passed. Thus, we can only confidently report that this moraine has been sublimating at a rate of 12 m Ma^{-1} and eroding at 0.4 m Ma^{-1} for the past ~0.4 Ma.

Quartermain till over Arena till (04-AV-Pit 6)

Given the age of the Quartermain I till (>2.3 Ma), we expect that the nuclide concentrations of both units would have come into equilibrium with the most recent period of exposure. Fitting a single erosion rate to both tills yields an erosion rate of 0.6 m Ma^{-1} , but the chi-square fit is 29. The erosion exposure model fits the samples from the Arena till very well, but the samples in the Quartermain I till have lower nuclide concentrations than predicted by erosion alone (Figure 4B), which suggests that the sublimation and erosion exposure model may be more appropriate for the Quartermain I till samples. The exposure model that we will test for this site is that the upper unit, the Quartermain I till, contained dirty ice and was subject to both sublimation and erosion, but that the Arena till did not have any ice. In this scenario, the Arena till measurements would record the same degradation rates as the Quartermain I till, but would not deflate due to the sublimation of ground ice.

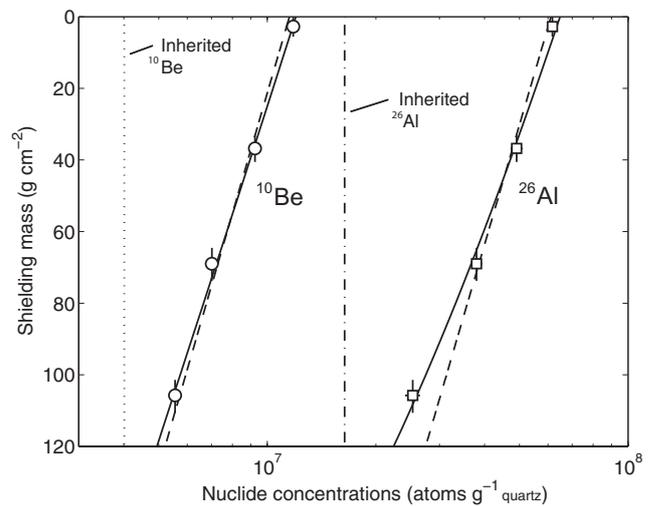


Figure 5. Nuclide concentrations for 04-BV-Pit 15, the Beacon Valley moraine, showing the best-fit predictions for the sublimation exposure model (solid line) and the erosion exposure model (dashed line). The dashed and dot-dashed vertical lines show the best-fit inherited ^{10}Be and ^{26}Al , respectively, for the sublimation exposure model. The sublimation exposure model captures the nuclide concentrations at all depths, but the erosion exposure model fails to explain the measured nuclide concentrations. The model parameters for the best-fit sublimation exposure model are (chi square = 3.2): the dirty ice initially had 12% debris, which sublimated at 12 m Ma^{-1} and the overlying till eroded at 0.4 m Ma^{-1} . Based on the effective half life of the nuclides, this site has been subject to these degradation rates for the past ~0.4 Ma. Inherited nuclide concentrations remaining in the till today of $4.1 \times 10^6 \text{ atoms g}^{-1}_{\text{quartz}}$ for ^{10}Be and $17 \times 10^6 \text{ atoms g}^{-1}_{\text{quartz}}$ for ^{26}Al .

The parameters for Equation 2 (Figure 6) that best match the measured nuclide concentrations for the Quartermain I till samples are that the till was deposited at 5.3–0.5/+0.3 Ma ago as a deposit of dirty ice with a debris concentration of $45 \pm 10\%$. This ice sublimated at a rate of $0.7 - 0.3/+0.2 \text{ m Ma}^{-1}$ and the resulting till eroded at a rate of $0.5 \pm 0.1 \text{ m Ma}^{-1}$. Under these degradation rates, the lowest sample at this site emerged from the ice at 0.25 Ma ago. The inherited nuclides remaining in the samples today in this scenario are zero for ^{26}Al and $2.6 \times 10^6 \pm 7.6 \times 10^3 \text{ atoms g}^{-1}_{\text{quartz}}$ for ^{10}Be . These degradation rates fit the measured concentrations in the Quartermain I till with a chi-square value of 4.0. These degradation rates match the Arena till data very well (chi-square = 2.7) with essentially zero inherited ^{26}Al and $7.9 \pm 1.4 \times 10^5 \text{ atoms g}^{-1}_{\text{quartz}}$ of inherited ^{10}Be remaining in the till today. This exercise demonstrates that the Arena till data are consistent with the sublimation and erosion rates from the overlying Quartermain I till, without having any ice in the Arena till. These results suggest that the Quartermain I till is older than 2.3 Ma, but based on the effective half-life of the nuclides at this site, we can only say that sublimation at a rate of 0.7 m Ma^{-1} and erosion at a rate of 0.5 m Ma^{-1} has been going on at this site for ~2 Ma.

Arena till (04-AV-Pit 16)

The measured nuclide concentrations for this site yield simple exposure ages of 400 to 600 ka, which indicates that the nuclide concentrations reflect the degradation rate at the site and not the exposure age. The parameters for Equation 1 (Figure 7) that best-fit the measured nuclide concentrations are that there is no inherited ^{10}Be or ^{26}Al remaining in the sample

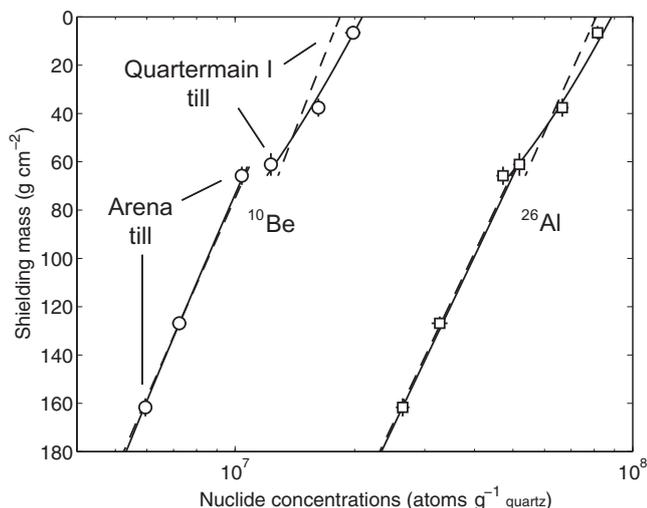


Figure 6. Nuclide concentrations for 04-AV-Pit 6, the site where the Quartermain I till overlies the Arena till, showing the best-fit predictions for the sublimation exposure model (solid line) and the erosion exposure model (dashed line). The data suggest that the Quartermain I till contained ice, but the Arena till did not. The model parameters for the best-fit sublimation exposure model are (chi square = 4.0): 0.7 m Ma^{-1} for the sublimation rate, 0.5 m Ma^{-1} for the erosion rate, 45% for the initial debris concentration, and inherited nuclide concentrations remaining in the till today of $2.6 \times 10^6 \text{ atoms g}^{-1} \text{ quartz}$ for ^{10}Be (too small to plot at this scale) and essentially zero for ^{26}Al . Based on the effective half-life of the nuclides, this site has been subject to these degradation rates for the past $\sim 2 \text{ Ma}$. The Arena till data are well explained by the degradation of the overlying Quartermain I till subject to these rates, with inherited ^{10}Be of $7.9 \times 10^5 \text{ atoms g}^{-1} \text{ quartz}$ and zero ^{26}Al remaining in the till today.

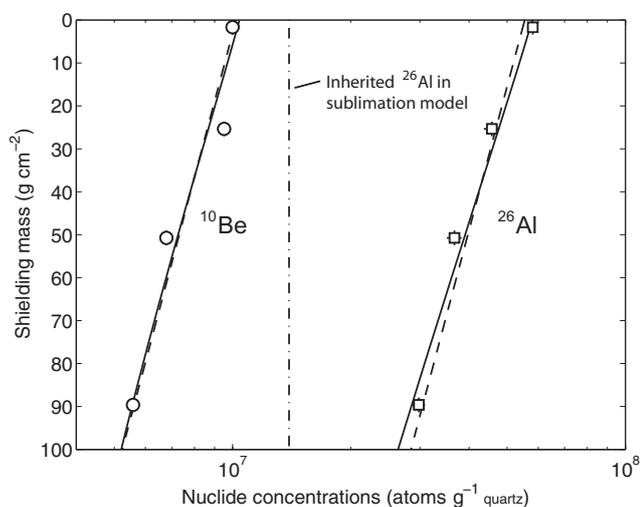


Figure 7. Nuclide concentrations for 04-AV-Pit 16, the Arena till, showing the best-fit predictions for the sublimation exposure model (solid line) and the erosion exposure model (dashed line). The dot-dashed vertical line shows the best-fit inherited ^{26}Al for the sublimation exposure model, and the inherited ^{10}Be ($3.3 \times 10^6 \text{ atoms g}^{-1} \text{ quartz}$) is too small to plot on this scale. At this site, the sublimation exposure model does not explain the data any better than the erosion exposure model and the best-fit results is that this site has been eroding at 1.2 m Ma^{-1} for the past $\sim 1.5 \text{ Ma}$, with no inherited nuclides remaining in the till today.

today and that the site has been eroding at a rate of $1.2 \pm 0.1 \text{ m Ma}^{-1}$ (chi square = 20). Though the ^{26}Al data show lower nuclide concentrations than expected by the erosion line, which is characteristic of a till formed by the sublimation

of ice, the ^{10}Be data do not show this same pattern (Figure 4C), and the sublimation exposure model does not improve the fit to the data (chi square = 20). Thus, the best-fit results for this site are that the Arena till has been eroding at a rate of 1.2 m Ma^{-1} for the past $\sim 1.5 \text{ Ma}$, which is the time period that these measurements record.

Discussion

At all of the sample sites, the measured concentration of cosmogenic nuclides are lower than expected given the age of the tills because the concentrations reflect the degradation rates of the deposits. Though ground ice was not found at any of the sample sites in this study, two of the three units that were sampled have cosmogenic nuclide concentration patterns consistent with a till that formed in part as a lag by the sublimation of debris-laden ice. The degradation rates that best fit the measured nuclide concentrations range from 0.7 to 12 m Ma^{-1} for the sublimation of ice and the resulting till eroded at a rate of 0.4 to 1.2 m Ma^{-1} . Previous studies using cosmogenic nuclides to determine ice sublimation rates through the Granite Drift in Beacon Valley calculated rates from 4 to 23 m Ma^{-1} (Schäfer *et al.*, 2000; Ng *et al.*, 2005), and regolith erosion rates in Arena Valley from 0.2 to 2 m Ma^{-1} (Putkonen *et al.*, 2008a; Morgan *et al.*, 2008). The results of this study suggest that some tills in the Quartermain Mountains begin with much higher debris concentrations, 12–45%, than what is currently found in the buried relict glacial ice in Beacon Valley, which is 3.1% debris by weight or $\sim 2\%$ by volume (Marchant *et al.*, 2002).

The time period that these nuclide concentrations record is limited by the effective half-life of the samples, which is dependent on the degradation rate at each site. Once several effective half-lives have passed, the cosmogenic nuclide concentration in a given sample will reflect only the degradation rate, and not the exposure age of the sample. This limits our ability to uniquely define an exposure age for these glacial deposits and limits our findings to the past ~ 0.4 – 2 Ma . However, this also allows us to confidently state that the nuclide concentrations reflect shielding by ice at some point in the past ~ 1 – 2 Ma because they have not come into equilibrium with the erosion rate yet. If these samples had accreted into the till $> \sim 1$ – 2 Ma , then their nuclide concentrations would reflect only the surface erosion rate. Though we cannot uniquely determine the depositional age of either of these deposits, the data indicate that the lowest sample at the Beacon Valley moraine accreted into the till 27 ka ago, and at the Quartermain I till the lowest sample emerged from ice at 250 ka ago.

The finding that some of these deposits are sublimation tills that began as debris-laden ice is consistent with the observation that many modern and recently formed moraines in the MDV are ice-cored (Debenham, 1921; Hall *et al.*, 1993; Denton and Marchant, 2000), and that till patches on valley floors can form by sublimation of dirty ice (Sugden *et al.*, 1995). The two sites that show evidence of containing ground ice were both deposited by cold-based ice and are the younger two drifts, suggesting that depositional process may affect the starting conditions for these tills. That the Arena till did not show conclusive evidence of containing ground ice may be related to the idea that wet-based ice deposited this till and it never contained ground ice, or that any ice this unit contained sublimed so long ago that the cosmogenic nuclide concentrations only reflect the erosion rate, which is possible given the significant age of this unit ($> 11.3 \text{ Ma}$).

At the Beacon Valley moraine site (Pit 15) we can constrain the model results with the geologic setting because this site is

at the crest of a moraine that has a width between 10–25 m from the crest to the toe of the south-eastern flank. In a cross-sectional profile, moraines are often modeled as having initial slopes at the angle of repose ($\sim 34^\circ$) with a triangular cross-section (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003; Putkonen and O'Neal, 2006; Putkonen *et al.*, 2008b). At the sample site today, the moraine is 25 m wide and 1.8 m high, giving it a slope of 4° . If we assume that the maximum height of the moraine is limited by the angle of repose, and that the moraine was initially 25 m wide, then the initial moraine height would have to be < 17 m, otherwise the slope would have exceeded the angle of repose. Given this starting point and the degradation rates determined for this site, the moraine cannot be older than 1.3 Ma. Putkonen *et al.* (2008b) suggest that ice-cored moraines may start with initial slopes less than the angle of repose, which would make the moraine younger, and indicates that the moraine likely correlates with the Taylor IVa (0.7 Ma) moraine in Arena Valley.

Though the model results suggest that ice was present at two of the sites, there does not appear to be any overturning of these tills due to cryoturbation during the time period that the measurements record (~ 0.4 , ~ 2 Ma). This is consistent with the lack of geomorphic features that would indicate cryoturbation at the sites (e.g. polygons, sand wedges) and the cosmogenic profiles over the Granite Drift (Schäfer *et al.*, 2000; Marchant *et al.*, 2002). These data are consistent with the idea that erosion at some sites in the MDV is limited to the upper few centimeters of the surface, and does not involve creep or vertical mixing (Putkonen *et al.*, 2008a). Because erosion at these sites occurs without creep or vertical mixing, the surface appears to simply lower over time. This would result in slopes that retreat in parallel, and may explain how many glacial deposits in the Quartermain Mountains maintain their meter-scale morphology for millions of years while uniformly eroding a few meters over that time period.

The measured nuclide concentrations suggest that degradation rates are steady on a $\sim 10^5$ year timescale because the effective half-lives of the nuclides range from 1 to 5×10^5 years. Sublimation and erosion rates are probably not steady on yearly timescales, and are likely punctuated by extreme events and periods of stability, but over $\sim 10^5$ years, these variations are indistinguishable from steady degradation. The development of a sublimation till over dirty ice is thought to shield the underlying ice from sublimation, and as the till layer thickens, sublimation rates should lower (Hindmarsh *et al.*, 1998; Schorghofer, 2005; Kowalewski *et al.*, 2006). The results of this study suggest that erosion of the overlying sublimation till may act to thin the till such that sublimation rates remain constant on a $\sim 10^5$ year timescale.

The age and stability of the relict glacier ice in Beacon Valley has been the subject of much debate and research (Sugden *et al.*, 1995; van der Wateren and Hindmarsh, 1995; Hindmarsh *et al.*, 1998; Marchant *et al.*, 2002; Ng *et al.*, 2005; Kowalewski *et al.*, 2006). The results of this study only record what has happened at the study sites for the past 0.4–2 Ma, and therefore do not directly address the preservation of ice that is 8.1 Ma. However, these results do indicate that glacial deposits that begin as dirty ice degrade due to steady sublimation and erosion on 10^5 year timescales. If erosion is lowering the surface at a rate close to that at which sublimation is lowering the ice front, then ice may persist near the surface. This result provides a mechanism for maintaining ice near the surface without needing to invoke any recharge mechanisms or changes to the climate and suggest that the relict glacier ice in Beacon Valley may only be covered by a thin (< 1 m) layer of till because this till layer is slowly eroding.

Conclusions

By analyzing the concentration of cosmogenic ^{10}Be and ^{26}Al in soil profiles from three glacial deposits in the Quartermain Mountains, Antarctica we addressed the apparent conflict between millions of years old glacial deposits that maintain their meter-scale morphology and contain ground ice. Even though we did not encounter ice during the excavation of these deposits, nuclide concentrations in Beacon Valley moraine and the Quartermain I till are best explained by the sublimation of debris laden ice and erosion of the overlying sublimation till. The degradation rates that best match the data range from 0.7 to 12 m Ma^{-1} for the sublimation of ice with initial debris concentrations ranging from 12 to 45% and erosion of the overlying till at rates of 0.4 to 1.2 m Ma^{-1} . Because nuclide concentrations reach equilibrium with these degradation rates on the order of 0.4 to 2 Ma, we cannot uniquely determine the age of these deposits, but we can establish that the lowest samples in the Beacon Valley moraine and the Quartermain I till emerged from ice as recently as 27 ka and 250 ka, respectively.

These results show that some glacial deposits in the Quartermain Mountains have evolved due to both the sublimation of ground ice and by erosion of the surface, but that degradation at these sites has occurred without any vertical mixing or soil creep. This observation may be part of the reason that glacial landforms, such as moraines, in the Quartermain Mountains stand in sharp relief even though they are millions of years old. Without vertical mixing or soil creep, these slopes may retreat in parallel, which would help to maintain their meter-scale morphology. As ice sublimates through a till layer the permafrost table will lower through a soil, and if the overlying till is also lowering due to erosion then the permafrost table may persist near the surface. Erosion of the units above ground ice or relict glacier ice may explain how this ice continues to lie beneath a thin layer of overlying debris even though it is actively sublimating, without a need to invoke recharge mechanisms.

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